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A multidisciplinary fractured rock characterization study at Raymond field site, Raymond, CA

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Abstract

A dedicated field site was developed and a suite of experiments were conducted in the Sierra Nevada foothills, near the town of Raymond, CA to develop and test a multi-disciplinary approach to the characterization of groundwater flow and transport in fractured rocks. A wealth of geologic, hydrologic and geophysical data was collected at the site using a variety of unique tools. A cluster of nine approximately 90 m deep boreholes were drilled at the site in a V-shaped pattern with an angle of 60°. The boreholes are spaced 7.5, 15, 30 and 60 m from the central borehole. Various geophysical and hydrologic tests were conducted in and between these boreholes. Integration of cross-hole radar and seismic tomography, borehole flow surveys and images from a new digital borehole scanner indicated that groundwater flow is mainly confined to a few sub-horizontal fracture zones. A unique suite of hydraulic tests were conducted, in which three to four intervals in each of the nine boreholes were isolated using pneumatic packers. Some 130 injection tests were conducted, and more than 4100 cross-hole transient pressure measurements were obtained. A computer algorithm was developed to analyze such massive interference data systematically. As a result of the analysis, an image of the fracture connections emerged, which is consistent with the geophysical data. High precision tiltmeters were effective in remotely characterizing the preferential flow path. Several radial convergent tracer tests were conducted by injecting a mixture of several conservative tracers and one sorbing tracer: deuterium, fluorescein, lithium bromide and polystyrene micro-spheres. Some differences between the breakthrough curves are observed, which may be due to possible differences among so-called "conservative" tracers. Some characterization tools were found to be more effective than others in locating flowing fractures. However, no single tool was almighty. Characterization of fractured rock is extremely challenging and requires a stepwise and well-thought approach, which is basically a good old scientific approach. Prediction of transport based on the characterization results is even more challenging and one should always bear in mind that it is virtually impossible to uniquely characterize a fractured rock. © 2000 Published by Elsevier Science B.V.

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1. Introduction

Many countries including the United States are considering geologic repository for disposing of high-level nuclear wastes. Most such repositories would be built in fractured rocks. Many groundwater contaminated sites are also fractured, where non-aqueous phase liquids (NAPLs) are often trapped in fractures and slowly release contaminants into groundwater. To assess the performance of a repository or to design a remediation plan for such

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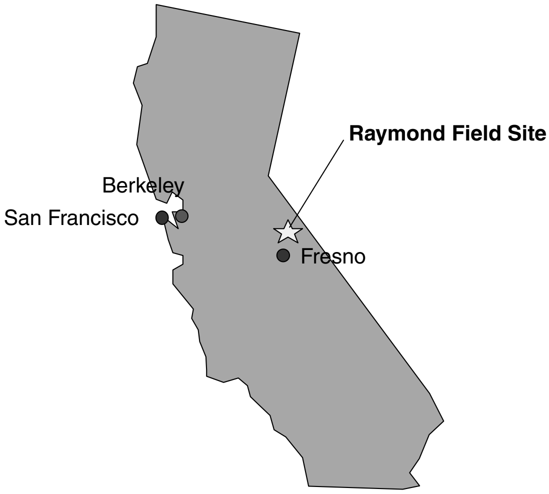

Fig. 1. Location of the Raymond field site near Fresno, CA.

contaminated sites, one must first understand the flow and transport system. However, characterization and prediction of flow and transport in a fractured rock mass is extremely difficult. The main reason for this is because the geometry of the flow path in a fractured rock mass is often very complex and heterogeneous, and therefore, very difficult to define. Field testing can be problematic for various reasons. The geometry of the fractures intersecting boreholes greatly influences test parameters and interpretation results (Karasaki, 1986; Cady et al., 1993; Shapiro and Hsieh, 1993). In a network of fractures, there are typically no definable upper and lower flow boundaries and only a fraction of the interval length in a borehole is open to flow. Moreover, the representative elementary volume (REV) may be much larger than the scale of the test, particularly for tracer tests (Endo et al., 1984). Assumptions regarding the flow geometry often have to be made a priori due to the lack of information. The analysis of the test results in light of necessary assumptions is difficult and non-unique, and often leads to model parameter estimates yielding large uncertainty in predictions of flow and transport. To improve field testing techniques and analysis methods for characterizing flow and transport properties of fractured rocks, a dedicated field site was established near the town of Raymond, CA. A variety of unique geophysical and hydrological tests were conducted at the site. In the present paper, we give an overview of the various studies conducted. For more detailed discussion of each study readers are referred to the corresponding publication cited in the paper. Similar fracture characterization site in granitic rock has been established at Mirror Lake in New Hampshire (Goode et al., 1993; Shapiro and Hsieh, 1993; http://toxics.usgs.gov/toxics/sites/mirror_page.shtml).

2. Raymond field site

The Raymond field site is located in the Sierra Nevada foothills, approximately 3.2 km east of Raymond, CA and 100 km north of the city of Fresno (Fig. 1). The site lies within the Knowles Granodiorite, which is light-gray, equi-granular and non-foliated (Bateman, 1992). It is widely used as a building material in California (Bateman and Sawka, 1981). The site is located on the land owned by the Coldspring Granite Company, which operates a quarry in the nearby area.

A cluster of nine boreholes were drilled and driller's logs indicate that relatively unweathered granite is located beneath less than 8 m of soil and regolith. The boreholes are laid out in a reverse V-shaped pattern with increasing spacing between boreholes (Fig. 2). Spacings of 7.5, 15, 30, and 60 m from the central borehole were chosen to allow the study of directional and scale effects on the flow and transport parameters. The angle between the southwest and southeast leg is approximately 60°. Two of the boreholes, SW-2 and SE-2, are reamed to 25 cm in diameter with the remaining boreholes being 15 cm. The boreholes are cased to approximately 10 m and vary in depth between 75 and 100 m. The water level is normally between 2 and 3 m below the surface.

3. Geological investigation

Detailed geologic and fracture mapping of exposed outcrops in the vicinity of the Raymond field site was constructed using the curved scan-line technique (Grossenbacher et al., 1997). The geologic map of the vicinity of Raymond field site is shown in Fig. 3. Zawislanski (1994) mapped fractures in the vicinity of the site with a particular focus on the distribution of pegmatite dikes. Mabee and Hardcastle (1997) attempted to correlate surface lineaments to subsurface hydrology. Quantitative analysis of fracture

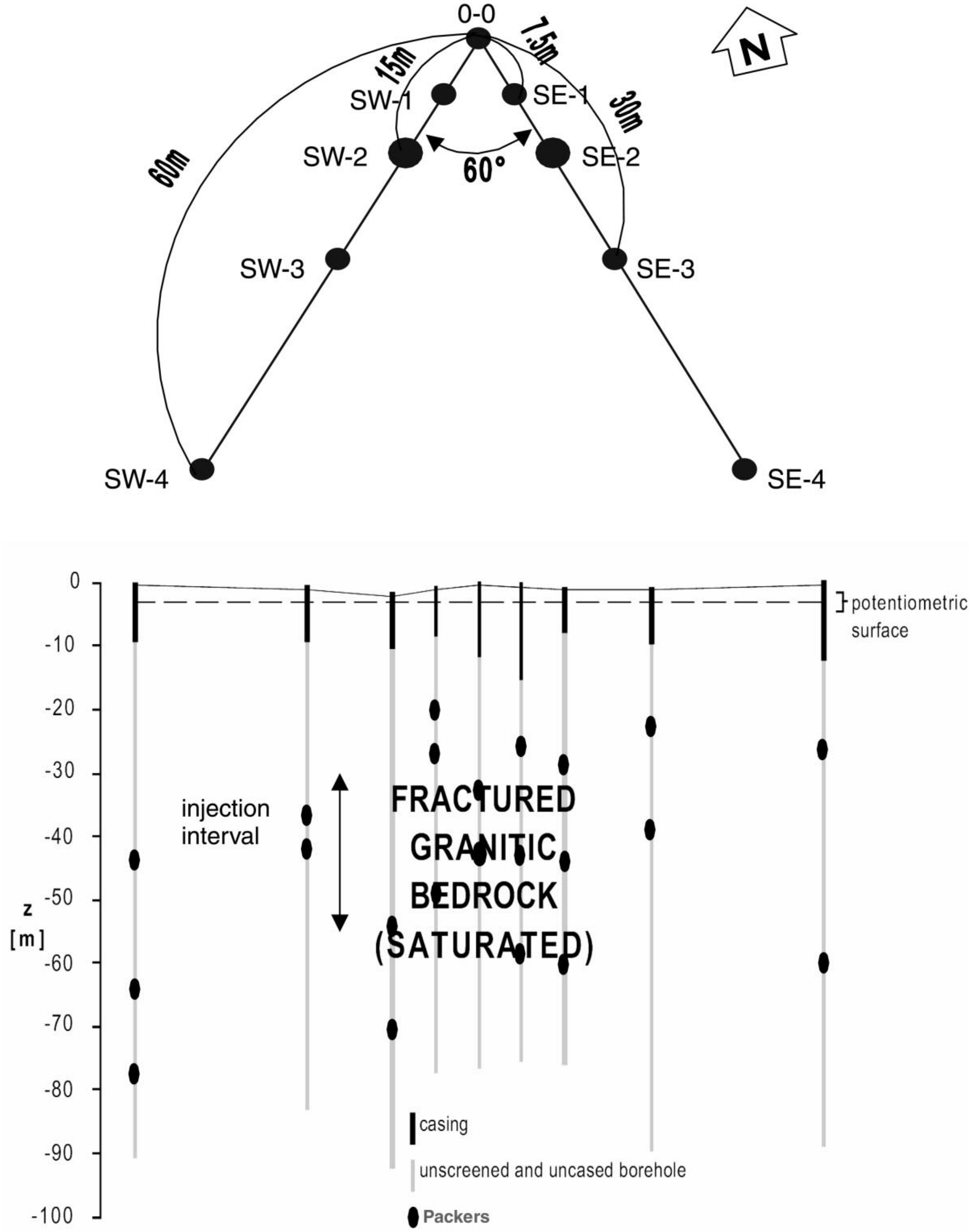

Fig. 2. Well configuration at the Raymond field site. Large bullets and small bullets indicate 25 and 15 cm diameter wells, respectively. Unfolded view of the wells show typical packer locations during the systematic injection tests. Note that the length of the injection interval is much shorter than the packed-off zones in non-injection wells.

intervals at 10 surface outcrops and in nine boreholes was conducted. Correlation study between grain size and macroscopic and microscopic fracture intervals and porosity was performed and it was found that there is a significant correlation between the two. Such surface fracture studies were necessary to augment the borehole fracture data that are biased against vertical fractures (Martel, 1999).

An abandoned quarry approximately 1 km west of the site provides a vertical exposure of the granite for fracture mapping and fracture coring. The quarry face was mapped extensively to supplement the fracture information at the well site. Surface profiles of large fracture surfaces were also collected at the quarry. Some profiles extend over 4 m, which is probably among the largest fracture surface profile ever taken. A method to digitize such data for statistical analysis was developed (Grossenbacher et al., 1996). Tectono-fractographic technique (Bahat, 1991, 1995, 1999) was then used to study the fracturing processes. The data are useful for modeling flow in fractures using actual data obtained at a much larger scale than a typical core. An innovative method of collecting fracture samples was developed to study in situ aperture and tortuosity of fractures. In this method a resin is injected into the fracture opening and after hardening of the resin, a core is drilled out with an intact fracture. The core is then cut diagonally to expose a fracture cross section and then made into a thin section. A photographic image can then be used to study alteration near the fracture, as well as digitized for waveform analysis of the fracture profile (Fig. 4).

4. Geophysical surveys and imaging

Geophysical logs included natural gamma, resistivity, acoustic televiewer (ATV), caliper and borehole deviation (Paillet, 1994). Benito (1994) correlated fractures observed by an ATV with those observed at outcrops. Cohen et al. (1996) evaluated various borehole characterization tools conducted at the site. Conventional television camera logs using fish-eye lens were run in all the nine holes. In addition, high-resolution digital borehole color scanner (BSS) surveys were conducted (Thapa, 1994). In contrast to the conventional borehole television survey, the BSS produces an unfolded image of the borehole wall at an extremely high resolution of up to 0.1 mm pixel. The image is stored in a digital format as well as on a VHS tape in an analog format. The digital image can be later processed to produce color hardcopies. Due to the digital nature of the image, various computer aided image analyses can be performed. Such analyses include an automatic fracture detection (Thapa et al., 1997) and fracture friction angle calculations (Thapa, 1994).

Two different types of intra-borehole flow surveys were also conducted in most boreholes. One was performed by using a heat-pulse flow meter (Paillet, 1994; Paillet et al., 1996). The other survey was conducted by first replacing the borehole fluid with de-ionized water and, subsequently, repeatedly running a conductivity probe down the borehole to monitor changes in the fluid conductivity under a pumping condition (Tsang et al., 1990; Paillet and Pedler, 1996). Fig. 5 shows a comparison of conventional geophysical logs and the fluid logging results from SW-1 borehole. Also shown is an image from the digital borehole scanner. The advantage of the optical scanner is that one can differentiate open fractures from filled or closed fractures. The heat pulse flow survey was useful in quantifying the inflow and outflow rate distribution (Paillet, 1998), while the fluid logging was particularly useful in pin-pointing inflow locations, i.e. the flowing fractures (Cohen et al., 1996). The latter was found to be even more effective when combined with the images obtained from the digital borehole scanner as shown in Fig. 5 (Thapa and Karasaki, 1996).

High-resolution cross-hole seismic tomography surveys were conducted between 10 pairs of boreholes. Results from the surveys conducted between the five boreholes closest to 0-0, (0-0, SE-1, SW-1, SE-2 and SW-2) were analyzed by simultaneously inverting the travel times and amplitudes (Vasco et al., 1996). Vasco et al. showed that there are two zones where both velocities and amplitudes are strongly attenuated: at a depth of 30 and 60 m. The 30 m depth coincides with the location of an anomaly identified by a ground-penetrating cross-hole radar survey (Korkealaakso and Okko, 1993). The radar tomography survey was conducted between SW-1 and SW-3 between the depths of 15 and 45 m. The results from the cross-hole radar tomography and the cross-hole seismic tomography are shown in Fig. 6.

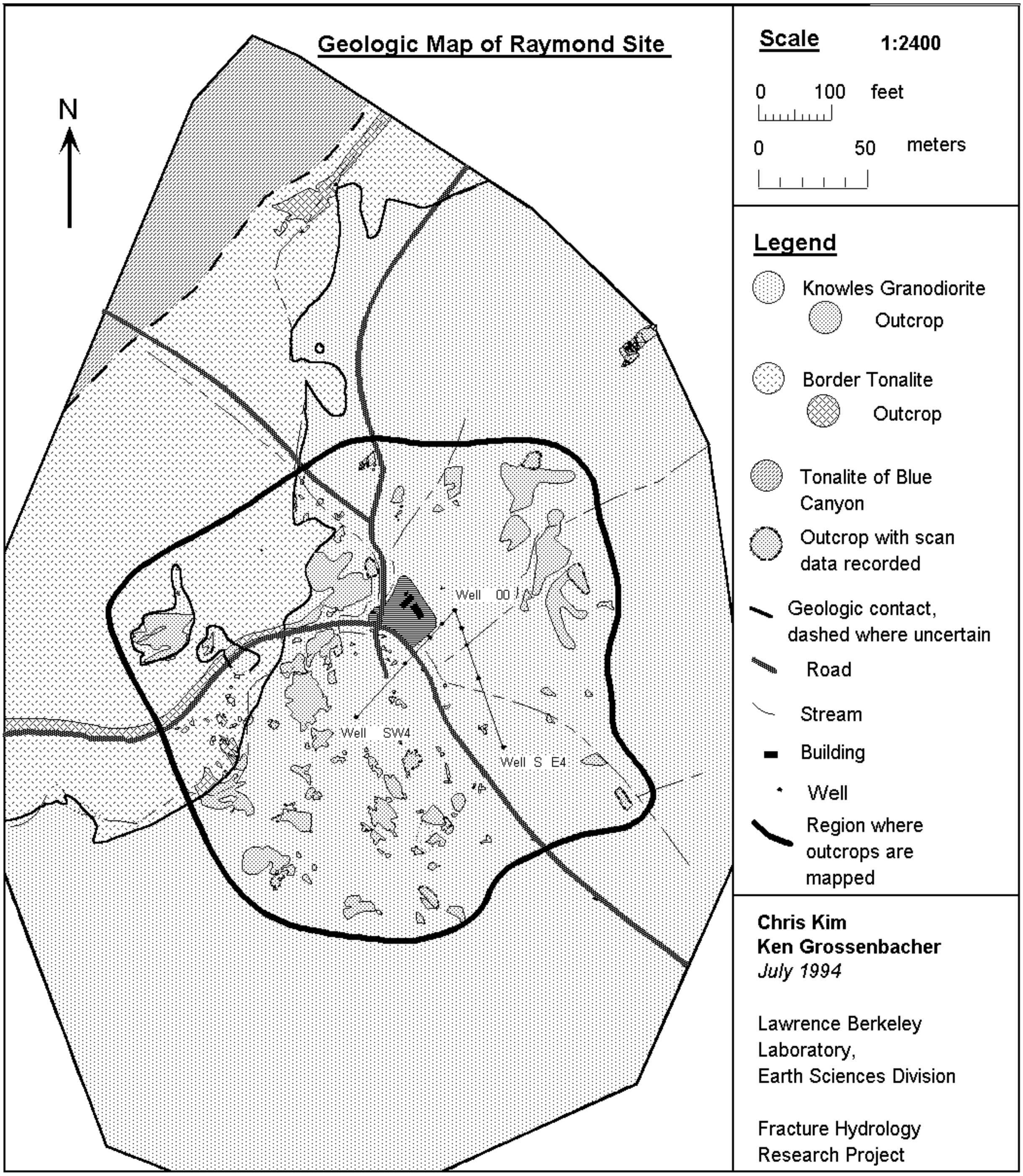

Fig. 3. Geologic map of the vicinity of the Raymond field site.

Three borehole logs, resistivity, ATV and caliper from SW1 and SW3 are superimposed on both ends for comparison. Both tomography results indicate that there is a major feature at a depth of approximately 30 m, although the two tomographies indicate different dip angle for the imaged feature. It should be noted that these surveys respond to different physical properties, i.e. the seismic method responds to a rock stiffness contrast, and the radar responds to the electromagnetic properties of the rock. The seismic tomography and the fluid logging indicate that there is another feature at a depth of approximately 60 m, for which radar tomography is not available. The information obtained by the geophysical surveys was used to determine the types of hydraulic tests and the locations for setting packers. It is shown in the following sections that the feature detected by the geophysical methods is indeed hydrologically significant.

5. Hydrologic data acquisition system

During hydrological field testing many parameters are both monitored and controlled simultaneously. At the Raymond field site, pressures are monitored in up to 29 different packed-off intervals while we simultaneously monitor flow rates and analyze water chemistry. To simplify the task of data acquisition and analysis, a new data gathering system was built around a PC. One PC controls an automated sampling table, opening and closing valves, and also logs pressure and chemical concentration data from all the measurement locations throughout the site. The ability to observe and manipulate the data collection in real-time was given a high priority in the development of the system. Unlike conventional data loggers, this allows interactive testing, so that any equipment problems can be quickly addressed. Also, controlled parameters such as flow rates can be adjusted while a test is underway. This is especially useful if monitored parameters start to fluctuate out of an allowable range.

Pneumatic packers are used to isolate zones in each borehole. In the 25 cm boreholes, SW-2 and SE-2, sliding head packers manufactured by TAM Corporation are employed, while in the remaining 15 cm boreholes, fixed-head packers made by Roctest are used. The packers have feed-throughs so that both fluids and electrical signals can be passed to the surface. In total, there are six TAM packers and 16 Roctest (fixed ends) packers creating the 29 intervals being monitored for pressure.

A schematic of the new data acquisition system is shown in Fig. 7. Data collection from up to 40 different transducers can be accomplished at a rate of 1 Hz. Analysis of fluorescent tracers is accomplished using a flow-through cell in a fluorometer and ionic tracer concentration is determined using ion specific electrodes. The output from these chemical concentration measuring devices are available in real-time on the computer. A computer-controlled sampling table with the capacity of 144 bottles, was built so that samples can be taken back to the lab for further analysis. In several months of field use, the fully automated data collection system has proven to be highly reliable, even for extended multi-week tests.

6. Hydraulic tests

Various kinds of hydraulic tests have been conducted. These include single well pump tests, falling head slug tests, pressure injection tests and several interference tests with various packer and pumping well configurations. Prematurely terminated slug tests (PTST) (Karasaki, 1990a,b) were also conducted in selected boreholes. In a PTST or systematic drill-stem test, a slug test is shut in or terminated before it completes and subsequent pressure recovery is monitored. Some pump tests were conducted without packers to investigate the effect of short-circuiting by boreholes (Cohen, 1993). In other pump tests the upper fracture zone in each borehole was isolated with packers. A minimum of two packers was used in each borehole with a total of 22 packers in nine boreholes. A total of 29 transducers were used to instrument each packed-off zone.

In one pump test, well 0-0 was pumped at a constant rate of 11 l/min. Fig. 8 shows the transient pressure data from selected intervals during the pumping. It is interesting to note that the intervals in wells 0-0, SE-1, SE-2, SW-1 and SW-2 display what looks like a unit-slope at early time whereas wells SE-4 and SW-4 have different transient characteristics from

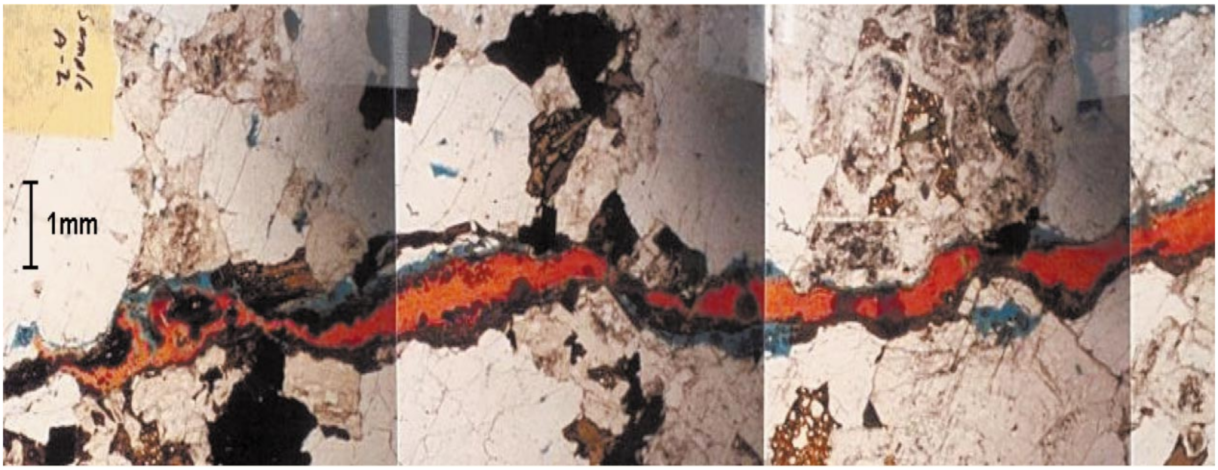

Fig. 4. The thin section of an open fracture captured by the resin injection technique.

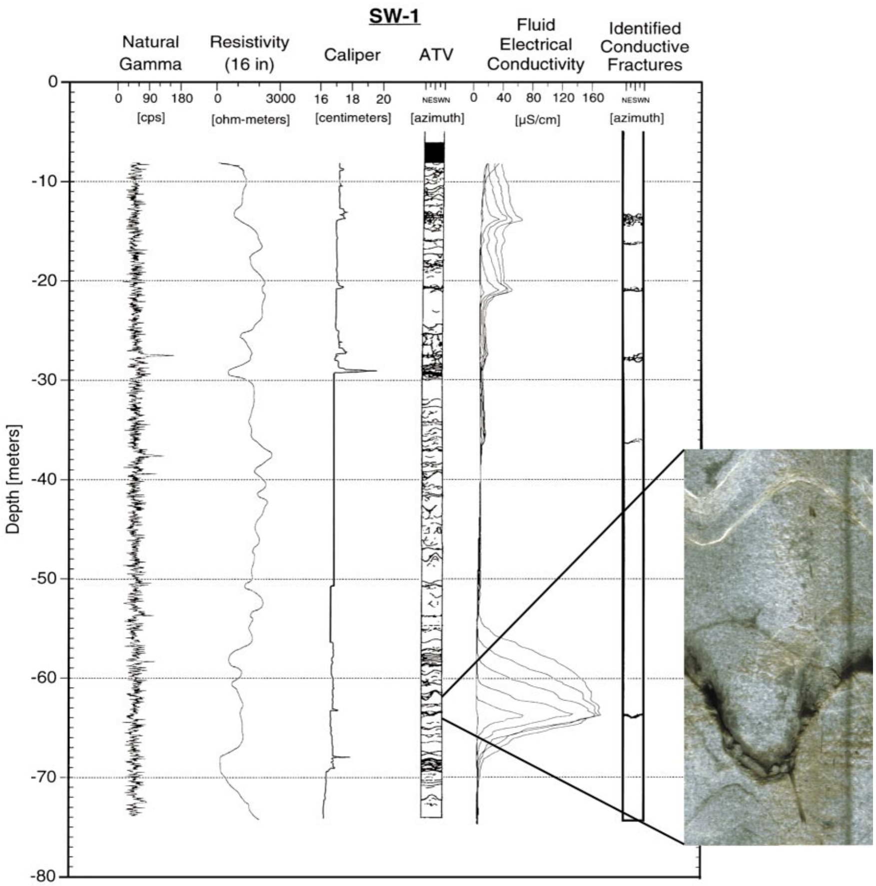

Fig. 5. Comparison of conventional geophysical logs and fluid logging results from SW-1. Note that although the ATV log indicates numerous fractures there are only few flowing fractures. High conductivity anomalies indicate the locations of inflow, i.e. flowing fractures. Also shown is a 1 m section image from an optical digital scanner. An open fracture is clearly visible and quartz veins appear as such.

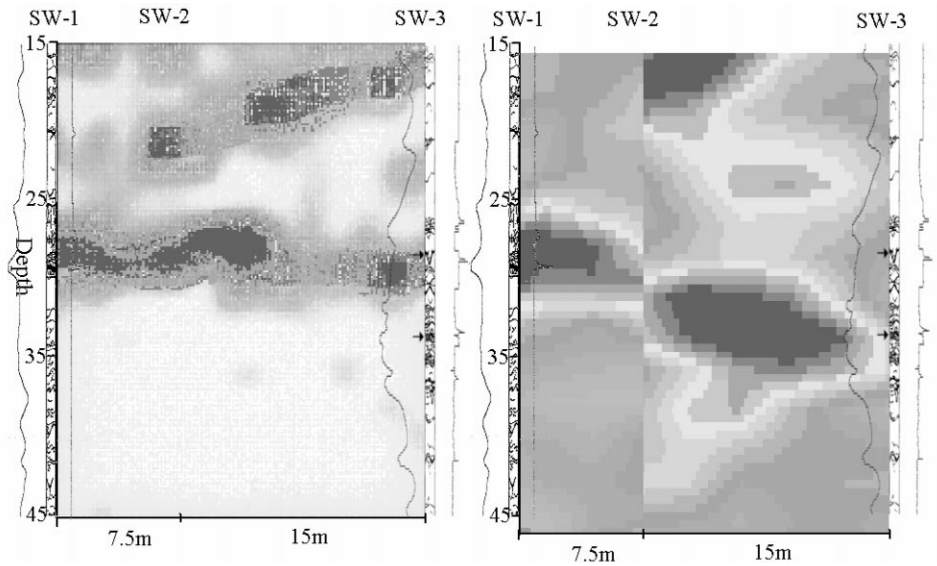

Fig. 6. Radar (left) and seismic (right) tomography results are shown with resistivity, ATV and caliper logs. Darker pixels indicate low velocity, and therefore, possible permeable fracture zones. The radar survey was conducted between SW-1 and SW-3, whereas the seismic survey was conducted from SW-2 to SW-1 and SW-2 to SW-3. The depth for the two surveys were offset by 1 m.

those of the other wells. It was postulated that the first four wells are intersecting a region with high permeability and low storage and that SW-4 and SE-4 lie outside of this region. The results from these tests indicate that flow is mainly confined in the two sub-horizontal fracture zones and that there is a high degree of heterogeneity within the zones. The finding that the sub-horizontal fractures are hydrologically active is not entirely surprising. The drawdown data as well as the tiltmeter surveys discussed later indeed indicate that there are preferential pathways within the fracture zone, which

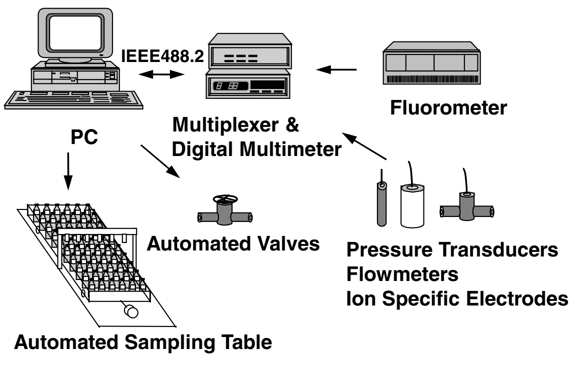

Fig. 7. Schematic of the control and data acquisition system.

means that the fracture is partially closed and partially open. It is possible that there are vertical fractures that are hydrologically significant and were not detected by the vertical boreholes. It does seem that it is the vertical fractures that hydrologically connect the two fracture zones.

Another observation is that the larger the time or the distance from the pumping well, the closer the pressure responses are in the upper and lower zone in a same well. This indicates that the features in the upper and lower zone identified by the geophysical logs are hydraulically connected with each other. Furthermore, a significant degree of heterogeneity within and among the wells was observed. Drawdowns in the SE boreholes are generally higher than in SW wells indicating preferred high permeability in the south-east direction. Results from the tiltmeter surveys discussed in the later section also indicate a preferential flow in the direction of SE boreholes. Some log–log time drawdown curves exhibit non-Theis characteristics that may be caused by non-uniform and discontinuous fracture connection. Some of the data, however, may have been affected by the very existence of the boreholes, i.e. the storage capacity and "conductivity" of boreholes are comparable or greater than those of the rock. Therefore,

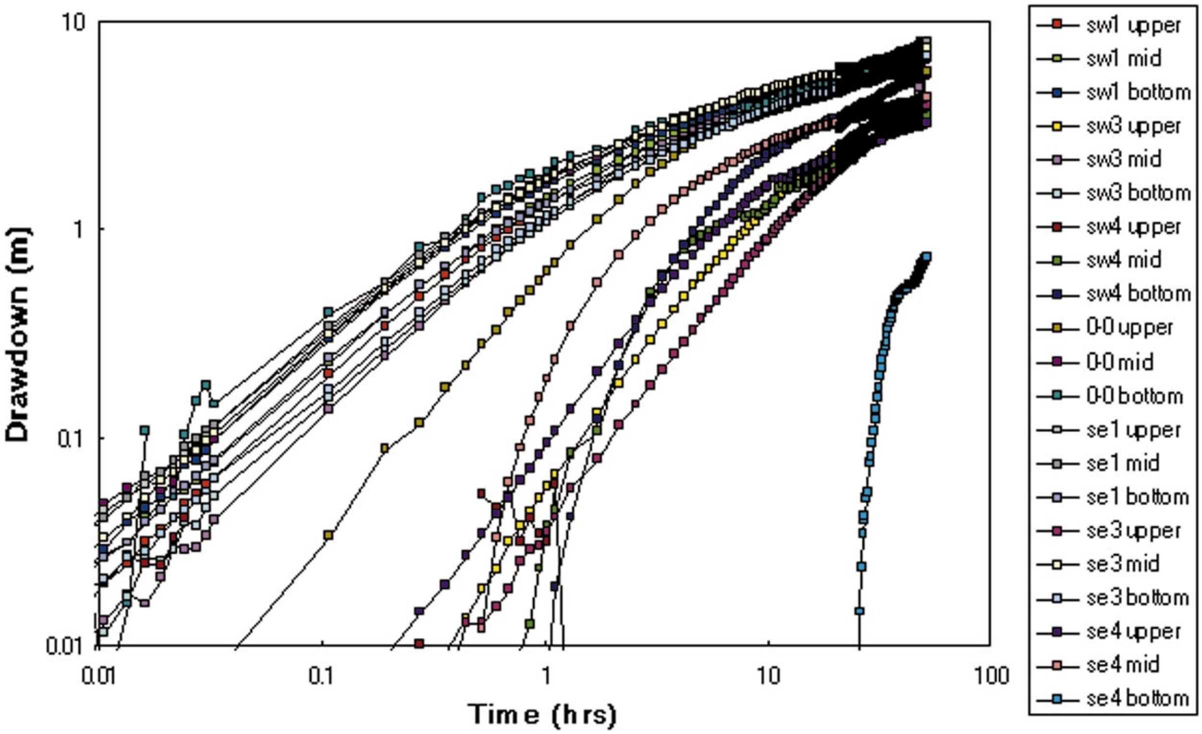

Fig. 8. Transient pressure from selected intervals during a radial convergent tracer tests. Note that the data are only part of what were recorded simultaneously.

observation wells may act like reservoirs and/or short circuit otherwise unconnected fractures.

7. Systematic injection tests and fracture connectivity analysis

Systematic injection tests were conducted in all nine wells. A straddle packer string with an interval length of 6 m was used to isolate and inject water into the packed-off interval. A pneumatically controlled downhole-valve was used to start and stop the injection. The pressure in the water tank was controlled and maintained at a constant pressure using compressed air. Neither the flow rate nor the downhole pressure was actively controlled; they spontaneously adjusted themselves accordingly to the transmissivity of the injection interval. In general it is easier to analyze the resulting transient data if either the downhole pressure or flow rate is held constant. The advantages of the present method are the simplicity of the set-up and the ease of test execution. A typical duration of an injection test was, on the average, 10 min. After each test, the packer string was lowered by approximately 6 m. Depth intervals sealed by the packers during a particular injection test were kept unobstructed during the next, so that the entire length of the well was tested. There were approximately 15 injection tests per well in all nine wells. While these injection tests were being conducted, the pressures in the remaining 31 intervals were simultaneously monitored. As a result, a total of some 4000 interference pressure transients were recorded. Fig. 2 shows an unfolded view of the well field and a typical packer configuration during the tests. An analysis of the injection data provides an estimate of the near-wellbore transmissivity distribution along each well, while the interference data provide information about interwell connectivity (Karasaki et al., 1994b).

To construct a hydrologic model using such a large number of interference data, a heuristic approach such as type curve matching would be impossible. With

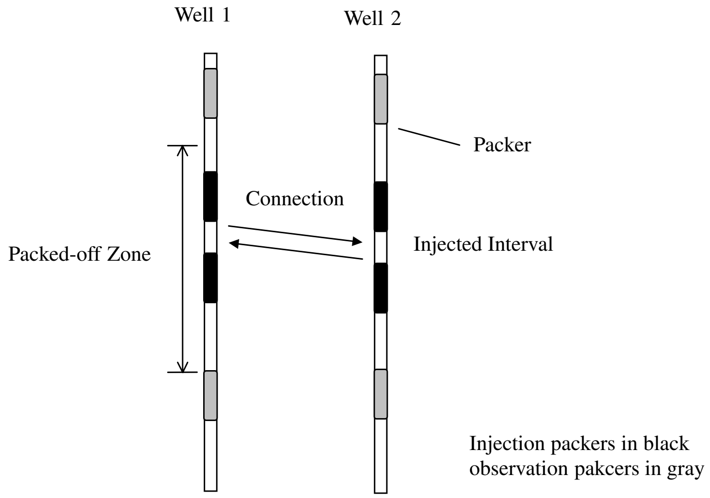

Fig. 9. Schematic of how connectivity is determined. For a hydrologic connection to exist between the length intervals straddled by packers shown in black, the packed-off zone in Well 1 should have a pressure response when the injection string is in Well 2, and vice versa.

nine wells there are 36 well pairs. With 15 injections per well there are 225 possible connections between each pair, which suggests that if the site geology were to consist of permeable porous rocks there would be 8100 connections to sort through. Some systematic approach is the only practical alternative. Full wave form inversion using the entire transient data (Mauldon et al., 1993; Nakao et al., 1999), however, would also be impractical, because as many as 135 forward simulations would have to be made for each iteration. A prohibitively large amount of computer space and time would be required to reach a reasonable answer.

To keep the computer time and size practical, and to still take advantage of such a large amount of cross-hole information, the binary inversion method was developed (Cook, 1996). In this method each set of interference transient pressure data was reduced down to a binary set: 1 (yes) if an observation zone responds to an injection; and 0 (no) otherwise. This method was later extended to incorporate the magnitude of pressure responses (Cook, 1996). In analyzing connections between wells, only the existence of a response has been investigated as a first step (binary inversion). The next step is to take into account the magnitudes of responses coupled with flow rates for injected intervals. These measures will have to be normalized not only to distances between wells but to heights between zones since some of the wells are so close together. By visualizing connectivity with various cut-off values, one can focus on features at different scales.

Each well had only three to four packed-off zones for observation, which does not lead to very high resolution when looking for possible connections. However, if the injected intervals (as many as 20 per well) are taken into account for pairs of wells, the resolution can be increased substantially. If (1) a given injection with a measurable flow creates a response in a packed-off zone in another well, and (2) this second well has an interval with flow somewhere in this zone when it is later injected and (3) this later injection in turn registers a response in the original well in a zone containing the original injection, then a note is made that these two injected intervals are hydraulically connected (Fig. 9). Since the injected intervals are roughly 20 ft in length, the method affords a 20 ft resolution per connection.

A computer algorithm that performs the logic described above and also keeps track of all the overlapping packer locations was developed. A further refinement to sorting for connections between pairs of wells was made to sort for shared connections in various combinations of wells. A routine that examines connections for N wells at a time works much like the two-well routine but searches for reciprocal responses in all N wells. For example, in a combination of three wells, a given injection interval would have to have responses in the other two wells. In

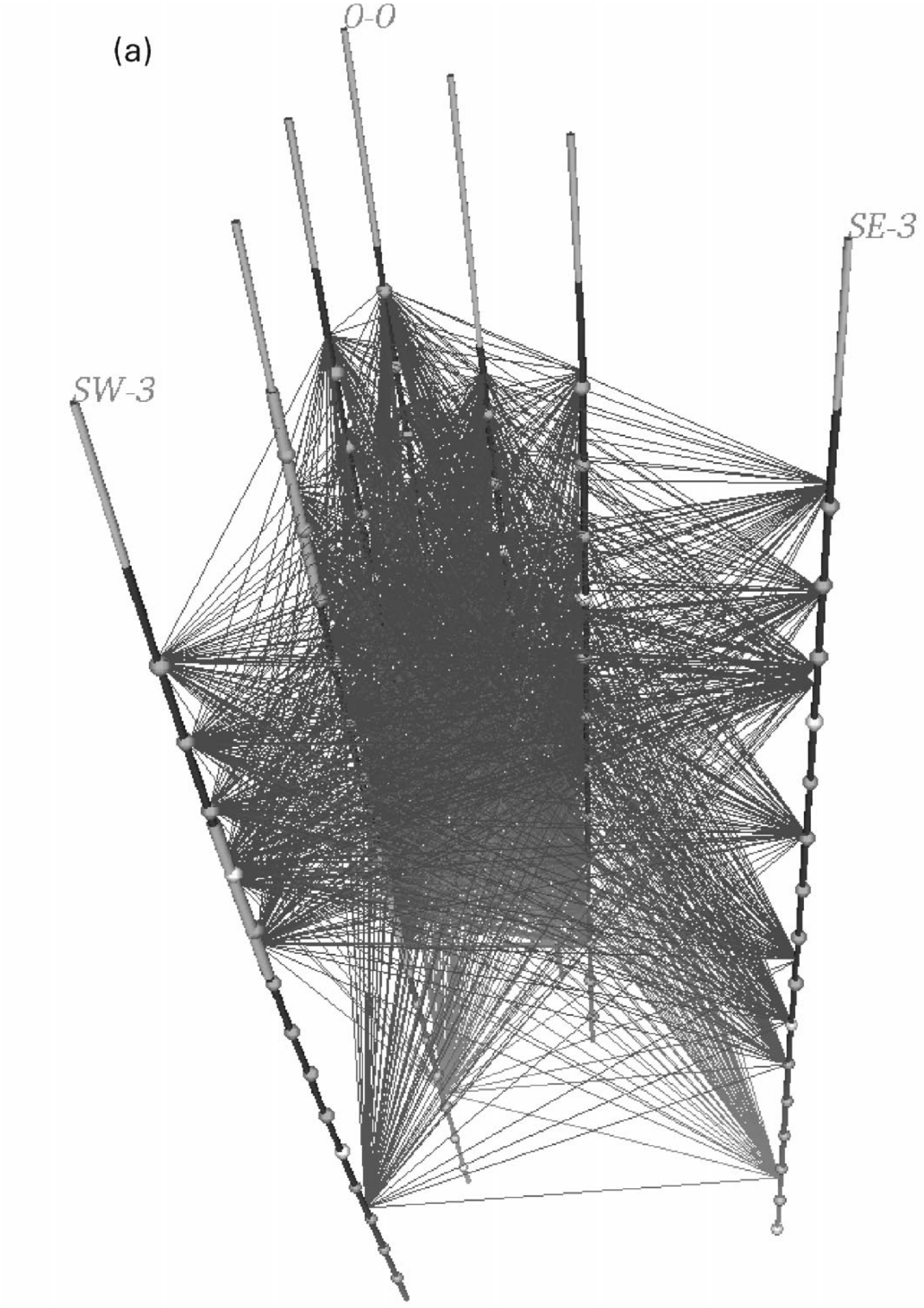

Fig. 10. (a) A perspective view of all the possible connections between intervals in the seven nearest wells. (b) The result from the binary inversion analysis. Note that the connections are sparse and are concentrated in the two semi-horizontal planes. Also note that there are more connections in the SE direction. The color indicates the strength of response normalized by the flow rate and distance.

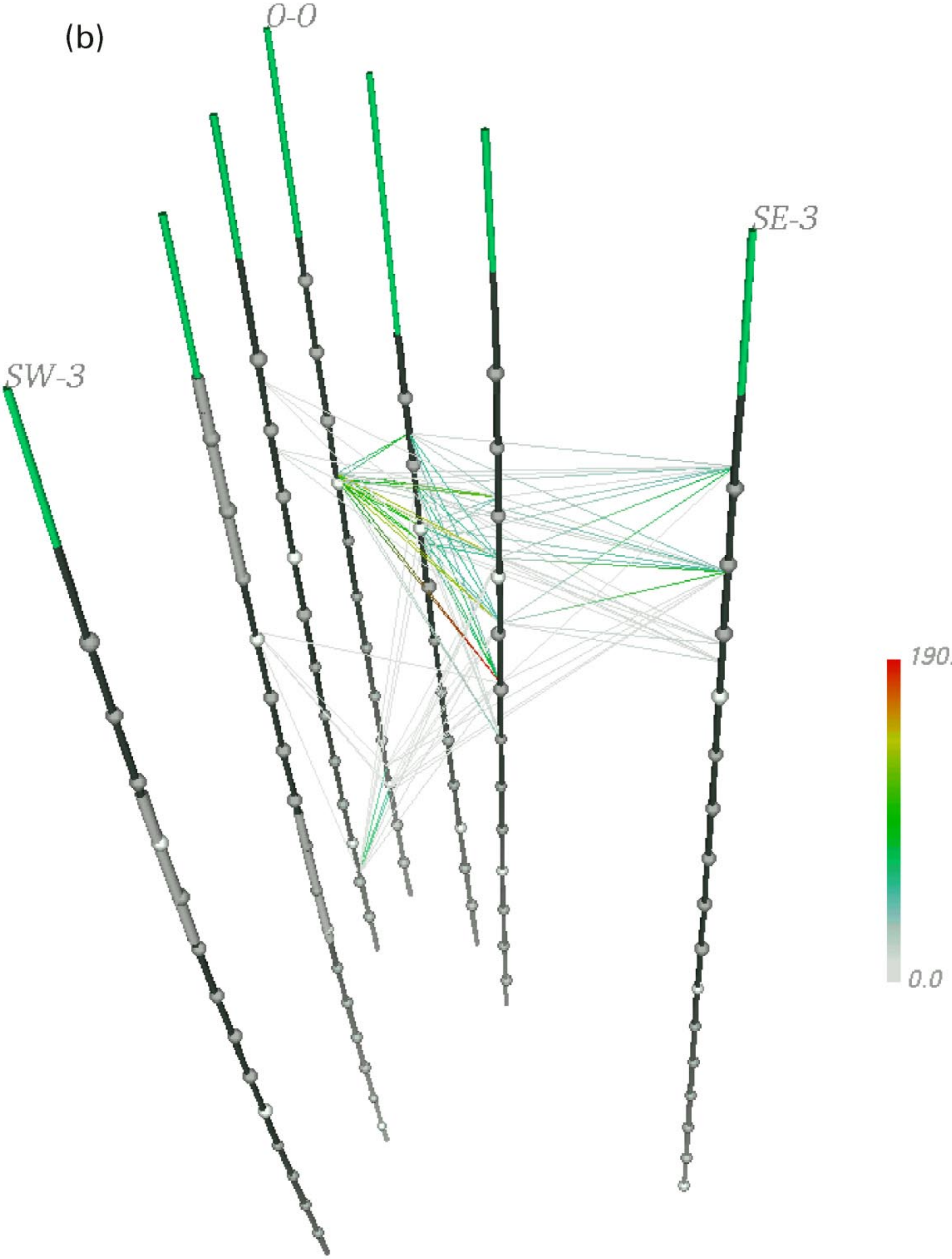

Fig. 10. (*continued*)

addition, these two wells would have to be connected to each other at those same response points. As the number of wells N is increased, the number of criterion tests for a possible connection increases proportionally to $N(N-1)$.

The 20 ft resolution and reciprocal connection criteria afforded by the injection test can be significantly enhanced by incorporating other data such as fluid logging. Fluid logging appears to pin-point the location of flowing fractures in wells within inches. Instead of using the center of an interval for connectivity analysis, we subsequently used the exact location of the flowing features and thus enhanced the resolution significantly (Cook, 1996). By doing so, we assumed that most of the flow occurs through fractures, which would be a reasonable assumption for fractured granite. In addition, we quantified the degree of connection by evaluating the magnitude of response normalized by the distance and the source strength.

Fig. 10a shows a perspective view of all the possible connections between intervals in the seven nearest wells. Wells SW-4 and SE-4 are excluded from the plot for clarity. Each line represents a possible connection between length intervals tested by an injection. Note the extreme density of lines indicative of the large number of cross-hole tests conducted. Fig. 10b shows the result from the inversion analysis. If the rock is a porous medium, we expect all the lines to remain after the analysis. However, as can be seen from the figure, the result is an image of two horizontal features, one at a depth of approximately 30 m and another at approximately 60 m. As noted in the previous section, these features correspond to those identified by the geophysical surveys. Another interesting result is the lack of connection between the features.

t should be noted that actual fracture connections or pressure propagation pathways are probably not straight lines. The lines in the figure merely indicate that there is a connection (in some manner) between two given length intervals. However, if there is a dominant feature such as a fracture zone in the present case, the lines would form a plane, effectively imaging the zone itself.

8. Tiltmeter survey

During the pressure tests, an interesting phenomenon was observed. While water was being pumped or injected in one well, opposite pressure responses were observed in some intervals in the wells in distance. For example, the pressure in the bottom interval of SE-4 increased initially while 0-0 was being pumped, and conversely, the pressure declined during the injection at 0-0. The phenomenon was completely reversible and repeatable. The possibility of electrical noise was ruled out. Cook (1996) postulated that this is due to the mechanical opening and closing of the fracture. To investigate such hydro-mechanical properties of the fracture zone, we monitored the surface deformation during pumping and injection using extremely high-precision tiltmeters. Tiltmeter surveys are commonly used to monitor hydrofracturing processes. Recently, they are beginning to be used to map reservoir flow geometry.

When fluid is produced from or injected into a reservoir, it causes volume changes in the reservoir, which in turn induce displacements on the ground surface. If the reservoir is horizontal and homogeneous, the induced displacements will be distributed concentrically around the production/injection borehole. In the case of the surface tilts, tilt vectors will be radially convergent to or divergent from the borehole. If a preferential flow path such as a fault zone exists in the reservoir, the distribution of the volume change and subsequent surface displacements will be skewed. An inversion algorithm can be used to estimate the distribution of the volume changes in the reservoir. The larger the volume change is at a particular location, the more fluid is likely to have moved in or out of the location. The distribution of volume change is tightly coupled with that of the reservoir flow properties: permeability and compressibility.

Nine high-resolution tiltmeters were placed in shallow holes and two were directly placed on the ground surface. A total of three surveys were conducted. In the first two tests, well 0-0 was pumped at two different flow rates, and in the third test, water was injected in well 0-0. All three surveys showed consistent results. As expected, tilt vectors were not concentric. The tilt amplitudes were larger in the SE direction. Vasco et al. (1998) inverted the tilts and the subsurface structure was revealed (Fig. 11). The results of the inversion show the distributions of the volume changes in the fracture zone at different times during the pumping. The region of large volume change extends toward SE direction, indicating a preferential

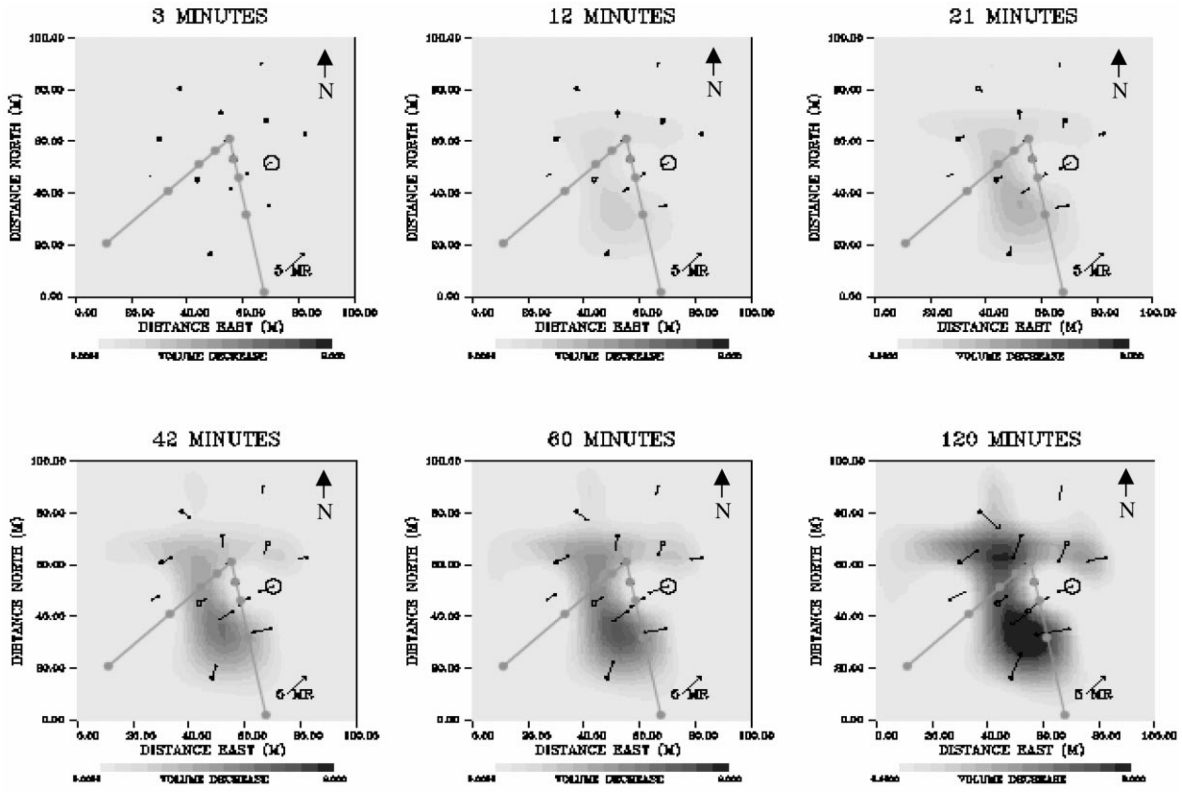

Fig. 11. Inverted volume change distributions in the fracture zone at six different times during the pumping. The darker color indicates larger volume change. The observed tilt vectors and the well configuration are also shown. In all tiltmeter surveys Well 0-0 (at the apex of the V) was pumped/injected.

flow in the direction, which is consistent with the cross-hole hydraulic test results discussed earlier.

9. Radial convergent tracer test

In a radial convergent tracer test, a well is pumped for an extended period of time prior to the test to establish a radially convergent flow field. Subsequently tracers are released from an injection well, or in some cases from multiple injection wells (Hodgkinson and Lever, 1983; Moench, 1995). We conducted a series of radial convergent tracer tests using several pairs of wells with varying distance and direction. Wells used are SW-3, SE-1 and SE-3 with 0-0 being used as the pumping well. Adjustments and improvements were made on each new test based on the experience gained in the preceding tests. We made adjustments in the types and amount of tracers, the tracer delivery system, and tracer analysis methods. Tracers used include: fluorescein, deuterium, fluoride, potassium bromide and lithium bromide. In some tests, polyurethane micro-spheres were also used as tracers (Karasaki et al., 1994b; Freifeld et al., 1995). All the tracers except for lithium are regarded as conservative tracers. It advisable to conduct batch tests to check the “conservativeness” of the tracers with the host rock and the injection plumbing.

Care was taken to minimize the volume in the injection interval and to mix the tracers well in the interval. We eventually chose to use a weak dipole system to enhance tracer delivery by re-injecting back 10% of the pumping rate. The rate was arbitrarily chosen and it is desirable to test at different rates as well. We also devised a separate plumbing system to re-circulate the

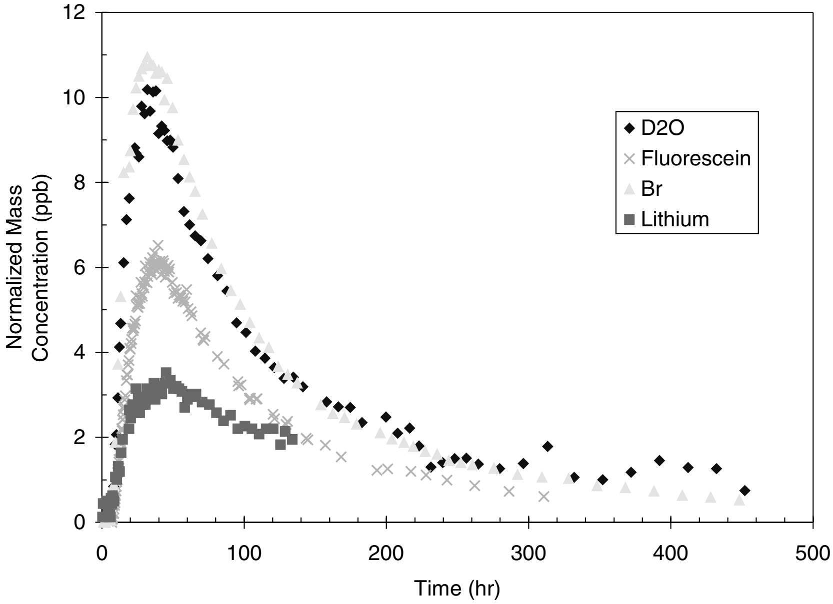

Fig. 12. Tracer breakthrough curves from the weak dipole radial convergent test from well SE-3 to well 0-0. Note that deuterium, bromide and fluorescein are "conservative" tracers.

fluid for better mixing in the injection zone. The flow field was still predominantly radially convergent.

In Fig. 12 the breakthrough curves from the test between SE-3 to 0-0 are shown. These wells are 30 m apart. We chose the upper fracture zone to inject tracers. As in the most other tests, well 0-0 was first pumped at a constant rate of 7.5 l/min for several days prior to the tracer injection to establish a quasi-steady flow field. About 0.75 l/min of pumped fluid was injected back into the injection zone. Tracer injection was done in three different stages. First, a tracer mixture of deuterium (1 kg) and fluorescein (1 g) was injected, 2 h later they were followed by lithium bromide (200 g in 2 l) and 4 h later by micro-spheres (0.36 μm diameter, 4.18×10^{13} spheres in 1 l). Lithium bromide was separated from other tracers because due to its higher density, bromide may cause the tracer mixture plume to sink to the bottom of the injection zone. The micro-spheres were separated because they were dyed with fluorescent dye, which might affect the fluorescein readings. The pumping continued for about 1 week, during which the pressure in all 29 zones and the flow rate at the discharge line were continuously monitored and recorded. Sample water was taken from the discharge line every 10 min using the automated sampling table for immediate fluorescein count and later ionic analysis in the laboratory. The first tracer arrival occurred at about 10 h after the injection. Samples were collected up to 450 h after the injecting. Peak arrivals were roughly 30–40 h after the injection.

The breakthrough curves of fluorescein, bromide, deuterium and lithium in Fig. 12 are the mass concentration normalized to the injected mass. The unit is dimensionless mass concentration in parts per billion. When compared to the tracer test results in the SW direction, the tracer arrived almost twice as fast in the SE direction. Although further analysis is needed, we obtained a twice as large apparent dispersivity as the test between SE-1 to 0-0, whose separation is 7.5 m. As can be seen from the figure three curves do not lie on top of each other, although these three tracers are presumably "conservative". It is surprising that fluorescein showed the lowest concentration. In another tracer test from SE-1 to 0-0, fluorescein had the highest concentration among the conservative tracers. It is not very clear why this is the case. Care was taken when making standards to avoid possible calibration errors. Fluorescein has been reported elsewhere to react with certain minerals in the rock, the rate of the reaction being pH dependent (Feunstein and Sellick, 1963; Deaner, 1973; Smart and Laidlaw, 1977). It is also known to degrade in sunlight (photodecomposition) and, conversely some organic growth in the discharge line or elsewhere gives apparent increase in the fluorescein concentration. Other possible scenarios for the difference in ionic tracers are that there may be differences in the degree of reaction (or non-reaction) among the tracers and/or these chemicals may have different mixing characteristics. After the tracers were injected, some tracer may have sunken in the injection zone, which is roughly ten times the volume of the injected fluid. It is also possible that the deuterium has diffused into the matrix more than bromide did. For microsphere results, readers are referred to Becker et al. (1999).

10. Summary and discussion

A dedicated field testing site for fracture flow and transport produced a wealth of data. Results of intraborehole flow surveys and cross-hole radar and seismic tomography surveys correlated very well with each other and identified a major feature at a depth of 30 m. It was found that by conducting a large number of short cross-hole injection tests and analyzing the connectivity, one can begin to image the hydrologic structure of a fractured rock mass. The feature identified by the connectivity analysis coincided with the one identified by geophysical methods.

A priori information obtained by geophysical surveys and geologic observations can be useful in designing subsequent hydrologic investigations. Correlations exist between surface features (such as pegmatite dikes, variations in grain size and contacts between different rock units) and subsurface features (such as highly conductive fractures or fracture zones). The packer configurations and locations can be set to pack off the features observed in the borehole geophysical survey. This was indeed the case at the Raymond field site. We began our hydrologic tests with uneven and irregular packer locations. As we conducted more tests, we learned more about the flow system. We then fine-tuned the packer configurations to tighten the packed off zone or moved the zone entirely. This was fine for the purpose of conducting each specific test. However, the fact that packer geometry was different for different tests made it very difficult to compare the results between the tests. This is because the boreholes themselves are perhaps the most hydrologically conductive features, and depending on the packer locations, the flow paths may be different each time.

Our experience thus far indicates that when conducting field experiments, particularly in a fractured rock, it is extremely important to make certain that what is being measured is actually what is intended to be measured. Wellbore conditions can alter conditions imposed at the surface, and an observation well can play a greater role than just as an access for measuring downhole conditions. One may end up measuring the "permeability" of boreholes rather than that of the rock or the wellbore hydrodynamic properties rather than the rock dispersivity.

Characterization of fractured rock is extremely challenging. Even with the level of effort outlined in this paper, we are not very confident that the model that is calibrated to the experiments thus far can adequately predict contaminant transport behavior under natural conditions. On the other hand, it is of interest to investigate how much effort is cost-effective and/or how much detail is necessary. This is dependent on the nature of the problem as well as the spatial and time scale of the problem. Sometimes it may be better to conduct few long-term/large-scale tests to let the system present its average behavior than to conduct many small scale tests and piece the results together to predict the behavior.

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